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NASA TT F-376

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by O. G. Gazenko and A. A. Gyurdzhian

Paper presented at the Eighth Plenary Meeting and Sixth International Space Science Symposium, Buenos Aires, May 10-21, 1965

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1965

NASA TT F-376

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PHYSIOLOGICAL EFFECTS OF GRAVITATION

O. G. Gazenko and A. A. Gyurdzhian[1]

ABSTRACT

The physiological effects of weightlessness are discussed, as they were measured and reported by the Russian cosmonauts. The possibilities of adaptation to space environment by training and the mechanisms of compensation and vicarization (adaptive substitution) of the analyzers and processes of the biological entity are considered. The authors present recommendations for cosmonaut training for distant and prolonged flights.

The physiological effects of weightlessness constitute a new and exceptionally important problem in the practical applications of space science. /2* They are also of great interest to theoretical physiologists. Weightlessness is an unusual experimental condition for investigating the general laws of the analyzer activity of the central nervous system and, therefore, the behavior and reactions of the organism to variable environmental factors.

However, it is our profound conviction that the physiological effects of gravitation cannot be correctly evaluated until we understand their significance in the general biological scheme of things, in the individual and evolutionary development of organisms, as one of the moving forces in evolution and as one of Earth's ecological constants. It will be remembered that in the course of evolution, living organisms have been exposed only to relatively brief inertial forces (accelerations), which were either added to the force of gravitation or were subtracted from it (jumps, drops, etc.). This was essentially the effect of shock acceleration.

It was not until the 20th century and the development of the technology involved in attaining high speeds that living organisms were subjected to prolonged acceleration or to low weight and to weightlessness. Future flights

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*Numbers given in the margin indicate pagination in the original foreign text.

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to other heavenly bodies with a larger or smaller mass than that of the Earth have created the possibility of man finding himself, under other gravitational conditions, exposed to high or low gravitation.

To our way of thinking, the fact that living organisms in the course /3 of evolution were not exposed to the prolonged effects of altered gravitational and inertial conditions must have left its imprint on the nature of their reactions. Presumably, the organism does not have ready specific mechanisms of adaptation to this factor, ready mechanisms of compensation and vicarization of impaired functions (as in the case of high doses of radiation which living organisms have similarly generally not encountered in the past). This situation must be borne in mind when analyzing the organism's reactions to altered gravitational conditions, and when considering the possibility of training persons to withstand prolonged or repeated accelerations and altered gravitational conditions.

A qualification is clearly needed here. We mentioned the effect of both gravitational and inertial forces, i.e., accelerations. The physical nature of these forces is, of course, different. However, as far as we know, they are completely equivalent to one another in biological effect.

This report will not examine the biological effect of such dynamic flight factors as relatively brief acceleration or vibration. We are mainly concerned with the reaction to prolonged weightlessness and, in part, to accelerations simulating the conditions of high gravitation.

The fundamental studies of Wunder, Vrabiescu et al., and several other investigators (refs. 15, 22, 51, 52 and many others) showed that raising /4 animals under the conditions of prolonged acceleration markedly affects morphogenesis, the formation of vegetative and animal functions and the reactivity of animals to a variety of accelerations. Further research is probably needed to elucidate in full the nature of these characteristics in experimental animals. Are they similar to the fairly well studied adaptive reconstruction of animals kept, for example, under hypoxic conditions, or do the characteristics of degenerative processes and changes prevail here? In any case, there is evidence in favor of the assumption that gravitational conditions, far from being insignificant biologically, play a highly important role.

Other matters of great interest are the relationship between the effects of high and low gravitation or weightlessness, and the possibility of extrapolating the results of experiments with prolonged acceleration to weightlessness and what corrections should be introduced in doing so. It is tempting to construct a unified theory of the effects of acceleration and weightlessness as physical factors belonging to a single category--gravitation (ref. 25). This question also probably will be answered after suitable biological experiments on spacecraft and after comparing the results with analogous laboratory investigations.

As stated, weightlessness is now the central problem relating to the biological role of gravitation from both practical and theoretical standpoints. Regarding the physiological effects of weightlessness, we unfortunately /5 possess only a limited amount of information, obtained under the following experimental conditions:

(1) manned flights on Soviet and American spacecraft (lasting up to five days);

(2) flights of animals and other biological objects on high-altitude rockets, earth satellites and spacecraft;

(3) experiments with brief weightlessness created on airplanes and on special apparatus (elevators, towers, etc.);

(4) investigations involving simulation of various effects of weightlessness (immersion in water, hypodynamic conditions, etc.).

The results of the flights of Voskhod and Voskhod-2 made a major contribution to physiology, especially the data on A. Leonov's walk in space. A short survey of the data and analysis of the materials available thus far on the physiology of weightlessness seems to us to be in order at this point.

There has been a definite evolution in the theory of the physiological effects of weightlessness. Until quite recently, prior to the first direct experiments in space, attention was focused largely on the possible unfavorable, direct influence of weightlessness as a physical (mechanical) factor on the principal physiological functions of the body: blood circulation, respira- /6
tion, eating and drinking, digestion and other processes, the starting point being the basic laws of hydrostatics and hydrodynamics (refs. 16, 18 and 19). However, the initial biological experiments on high-altitude rockets, artificial satellites and spacecraft showed that the changes resulting from the direct effects of weightlessness on the various systems were minimal and readily neutralized by adaptive and compensatory mechanisms (refs. 36, 37, 41, 42 and 47).

Later, when the possible physiological effects of weightlessness (and of acceleration) were analyzed, the attention of investigators began to be drawn to reflex mechanisms and to the interaction of the different sense organs.

Studies-in-depth were made on the dynamics of regulation of blood circulation during acceleration, low weight and under conditions simulating individual effects of weightlessness (immersion in water, adynamic conditions, etc.).

Many authors elucidated the relations between the individual sense organs (analyzers under weightless conditions). They obtained valuable information on the interdependence of the visual, vestibular and proprioceptive analyzers (refs. 23, 32, 60 and others).

Special attention was directed to the sensitivity of the vestibular analyzer. Some investigators assumed that, according to the well-known views of Weber and Fechner, its sensitivity would increase sharply in weightlessness. Thus, due to the interaction of the individual parts of the vestibular ap- /7
paratus (otoliths, semicircular canals), even slight accelerations might cause a marked sensorimotor reaction (refs. 20, 32, 45, 46 and others). However,

some investigators maintained that vestibular sensitivity would be unaffected or even diminish in weightlessness. This was the conclusion of those who studied human beings exposed to weightlessness on airplanes (refs. 42, 54), although the brevity of the weightless state and the effect of acceleration alternating with weightlessness naturally limited the value of the results obtained.

This problem, it can be readily appreciated, has a great bearing on the practical needs of space science in developing artificial gravitation systems (refs. 27 and 28) and in devising preventive and training measures.

Unfortunately, the matter cannot be settled on the basis of the results of the space flights to date. On one hand, G. Titov and B. Yegorov observed that abrupt head movements and optokinetic stimuli aggravated their general condition and caused some vestibular-autonomic disturbances, but without a pronounced nystagmic reaction (according to Yegorov).

On the other hand, the cosmonauts on Voskhod and Voskhod-2 noted that their general condition and efficiency had little to do with stabilization or rotation of the craft around its axis (about 1 rotation in 20-40 sec). When outside the cabin, Leonov did not experience any autonomic disturbances /8
due to vestibular and optokinetic stimulation during rotation of the body in different planes with a fairly high angular velocity. Moreover, investigation of the electric sensitivity of the vestibular apparatus (to a galvanic current) on board the Voskhod also supports the view that vestibular sensitivity is not intensified by weightlessness. However, it was a question here of sensitivity not to adequate, but to electric stimulation, and we are inclined to think that the subject requires further study.

There is no doubt that the starting point for analyzing and understanding the complex and varied picture of the physiological effects of weightlessness must be the reaction of the organism as an integral entity. It is essential to take into consideration its individual characteristics as well as its entire life's experience to date. I. P. Pavlov's synthetic principle may serve as Adriadne's thread in finding the right path in the labyrinth of the highly complex relations between the organism and the environment.

Accordingly, we should like to examine the physiological effects of weightlessness under the following aspects:

(1) sphere of afferent impulses and analyzer activity;

(2) efferent sphere, coordination of movements;

(3) sphere of regulation of autonomic functions.

Sphere of Afferent Impulses and Analyzer Activity

It is a well-known fact that spatial analysis is affected by the complex, integrated activity of all the analyzers--vestibular, visual, auditory, /9 motor, cutaneous, interoceptive, etc. The role of the individual analyzers varies with the level of evolution of the organism, ecological conditions of its habitat and preceding life's experience (ref. 50). Depending on these conditions, any given analyzer may play a leading role in the living organism's activity. L. A. Orbeli stressed the significance of "leading afferentation" in animal behavior (refs. 12 and 35).

Another point worth special mention is the exceptional role of the motor analyzer. I. M. Sechenov noted some time ago that the motor analyzer is the base on which all our afferentation, our entire perception of the external world, rests (ref. 43). In recent years, E. Sh. Ayrapet'yants emphasized the importance of the motor analyzer in spatial analysis. However, I. S. Beritashvili is of a different opinion, maintaining that the vestibular analyzer is the major element in spatial orientation (refs. 3, 4, and 9).

The vast capabilities for compensation and vicarious functioning of excluded analyzers are of particular interest in the mechanism of spatial analysis. This phenomenon of some analyzers substituting for others is by no means a single event, but a complex process requiring time and training. /10
For example, simultaneous enucleation of both eyes of an animal prevents the animal from making a conditioned jump, but when the operation is carried out in stages, this coordinated act can be preserved, i.e., the motor analyzer takes over, step by step, the functions previously performed by the visual analyzer (refs. 6 and 7). This explains, for example, how vision gradually comes to assume the leading role in afferentation in pilots undergoing training for blind flights. It also accounts for the variety of subjective reactions (sensations) to weightlessness (refs.14, 23, 53 and 55).

Some cosmonauts experienced no illusions of unusual bodily position in space, and the onset of weightlessness was detected from the "floating" of objects and "feeling of lightness." Others (G. Titov, A. Nikolayev, P. Popovich) immediately experienced illusory sensations of wrong bodily position in space ("upside down") on the shift from acceleration to weightlessness. Still others (K. Feoktistov and B. Yegorov) experienced these sensations (head or face down) some time later and retained them whether their eyes were open or closed (refs. 3, 36 and 37). The cosmonauts regarded the sensations as somewhat uncomfortable, rather than acutely unpleasant or intolerable.

Of great interest are the data testifying to the good spatial orientation of the cosmonauts on Voskhod-2, particularly that of Leonov while exiting from the cabin and when outside.

In the cabin, "up-and-down" was determined from interior furnishings, /11
and even while the vehicle was rotating relative to the orbital plane ("tumbling") the cosmonauts did not experience the upside-down sensation.

The tentativeness of the "up-and-down" idea as well as the practical necessity for precise orientation outside the spacecraft required the selection of a system of coordinates that would take into account both its long axis and the Sun's position. Orientation was also facilitated by the fact that the motion picture camera was on "top" of the airlock chamber. While in the latter, Leonov found the task of orientation difficult, but he had no disagreeable sensations. After leaving the cabin, he used the system of coordinates in accordance with the predetermined plan. However, if the craft did not fall within his visual field, spatial orientation became impaired and it was difficult to determine quickly the true location of the craft. On the whole, we have the impression that Leonov adequately assessed the situation, and though it was wholly novel and unexpected, he did not experience serious nervous tension or emotional stress.

All this shows the importance of previously selected visual orienting points and appropriate preliminary training. It seems to us that it confirms the great potential for reorganizing and training the mechanisms of spatial analysis. Visual information about the location of objects in space suppressed, so to speak, unexpected vestibular signaling, "sets in order" in- /12 formation from the sense organs and enables man to determine accurately the position of his body in space.

After his flight, Titov reported that with muscular tension the disagreeable vestibular-autonomic sensations disappeared almost entirely. Feoktistov and Yegorov had the same experience. In this situation, proprioceptive afferent impulses from the muscles evidently suppressed the unusual vestibular signaling. Cutaneous reception also clearly played a part (refs. 23, 24 and 34).

Presumably, the illusions and disagreeable vestibular-autonomic phenomena arising from unusual vestibular signaling (and, perhaps proprio- and interoceptive signaling) become more apparent against a background of a general poverty of afferent information. Adequate tone of the reticular formation and cerebral cortex seem to be beneficial (ref. 2). This may be the reason that the increase in total number of afferent signals during muscular contractions and motor activity markedly improved the condition of the cosmonauts.

In point of fact, Titov, Feoktistov, and Yegorov felt disagreeable vestibular-autonomic sensations and mild nausea (Titov and Yegorov) several hours after the launching and, although these did not interfere with execution of the planned program, they persisted almost throughout the flight. But the cosmonauts felt much better after sleeping. Disagreeable sensations did /13 not appear in Belyayev and Leonov, who performed very active work entailing considerable nervous, emotional and physical strain.

Thus, besides signs of adaptation and reconstitution of neural paths to cope with the new gravitational conditions, there were also indications of cumulation of disagreeable signals and rupture of the adaptation mechanism. The tone of the central nervous system was a matter of considerable importance, as revealed by the improvement after sleep and by resting the nervous system. It is probable that from the standpoint of tolerance of the unusual state of weightlessness, semidrowsiness is quite unfavorable. An active, wakeful cortex and the state of deep sleep inhibition of the entire cortex are apparently optimal. The level of the working apparatus has a significant effect on the reactions of the cosmonaut. Under certain conditions, the working dominant is a major normalizing factor. For example, despite the unusual flight conditions and "exit" into space (while Leonov was going through the air lock and while outside the cabin), the working apparatus clearly "suppressed" the disagreeable sensations that could have developed and overcame the impairment of spatial orientation by weightlessness.

Spatial illusions are undoubtedly due to the unusual interaction of the analyzers, the unusual combination of signals from different receptors. The reason may be that the weight of the body and objects disappears, while their mass and, consequently, their inertial forces persist. The illusions dis- /14 appear when new coordination of information from the analyzers is achieved, aiding in correcting spatial orientation. They seem to be a symptom of the transition from one type of coordination in the analyzer sphere to another.

Unusual signals from the visceral receptors and unusual combinations of signals between the different interoceptive zones and between the intero-, proprio-, and exteroceptors also play a definite part in the origin of vestibular-autonomic disturbances (refs. 1, 40 and 59). These examples show that the analyzer activity of the central nervous system in weightlessness can be best understood in the light of L. A. Orbeli's theory on the interaction of afferent systems. He treats this interaction as a plastic functional systematization of the work of the analyzers, with a great capacity for establishing new coordinations, which ultimately lead to the fullest and truest reflection of the external and internal (visceral) world in our consciousness (refs. 30 and 35).

Effector Sphere, Coordination of Movements

Coordination of movements is affected both by altered mechanical conditions (lack of weight with the retention of mass and, consequently, inertial phenomena) and by change in afferent impulses, which make correction of movements by the feedback principle difficult. The adjusting and postural-tonic reflexes, the base on which all other motor coordinations rest, are drastically changed by weightlessness. Furthermore, in free space the absence of points of support creates new conditions for biomechanics.

The results of studies on brief weightlessness in airplanes and ef- /15 fects of acceleration showed that the capacity for compensation and rapid restoration of coordination of elementary motor acts is great (refs. 17, 29, 36, 49 56 and 57). The cosmonauts' handwriting also improved from orbit to orbit (refs. 14, 33 and 37).

In our opinion, the possibilities of performing complex actions which are controlled by the cerebral cortex, which possesses a large capacity for adaptation, compensation and vicarious functioning, are even more favorable. In fact, the cosmonauts on Voskhod and Voskhod-2 had no trouble in performing the programed manipulations or in coordinating their movements. However, analysis of the time spent on some of the operations (handling the equipment, carrying out plethysmometry, etc.) showed that somewhat more time was required at the start of the flight than on the ground or at a later time in the flight. For example, during the first orbit Komarov needed about twice as much time to perform the operations involved in orienting the spacecraft as he did on subsequent orbits or when on the ground. This was also the case with Yegorov in taking physiological measurements. This phenomenon may very well be due to the effect of "external inhibition," resulting from the novelty of the situation and from the reconstitution of skills to suit the conditions of weightlessness. During later stages of the flight these phenomena generally leveled out or were compensated.

Investigation of the resolving power of the visual analyzer (with allowance made for the substandard lighting conditions) showed that it did not change appreciably. Operational visual efficiency occasionally decreased, but not significantly. /16

Investigations on the dynamic characteristics of the operator in a model control system are highly interesting. Use was made of graduated, random and sinusoidal signals with certain frequency characteristics. The operator (cosmonaut) was able to exert control by direct and delayed feedback in the system. The operator's standard deviation was greater during flight than during training in a mockup of the spacecraft. It was more pronounced with higher frequencies of the signal (fig. 3). Yegorov also concluded that in general, efficiency may be less in certain flight situations than when performing the same type of operations on the ground (time required and quality of the work). It was also demonstrated that the dynamics of well developed elementary skills was not impaired during the performance of programed operations. Thus, the data show that the cosmonauts retained a sufficiently high level of efficiency to ensure complete execution of the varied flight program.

The extravehicular behavior and movements of Leonov are exceptionally interesting. The data have important implications for the future, e.g., in assembling space objects. It is worth noting that in weightlessness even a comparatively slight exertion can cause the body to spin in different planes at a fairly high angular velocity, as confirmed by the motion pictures taken during the walk in space. /17

Preliminary biomechanical analysis of the characteristics of Leonov's movements outside the cabin (and on the ground on a special stand) reveals quite satisfactory coordination and the possibility of carrying out planned movements and actions with the tether. The cosmonaut succeeded in doing everything required to ready the camera and to dismount it before returning to the spacecraft. All operations were executed manually with no apparent difficulty.

The cosmonauts' nervous and emotional state and sleep during all flights, including the last one, were within normal limits.

These findings are highly encouraging from the standpoint of extravehicular activity.

In selecting cosmonauts, it is essential to take into account the individual capacity to reconstitute the existing coordinations in both the afferent and efferent spheres. The training program must be designed to develop this capacity.

We believe that in studying the capacity for reconstituting coordinations and substituting some for others, we can be greatly aided by the works of L. A. Orbeli and his school (ref. 35). They maintain that in establishing biologically new coordinations, old ones are suppressed with partial use made of some of their individual elements. The cerebellum warrants special attention. Orbeli thought that one of the functions of this organ is to suppress old coordinations in order to establish new ones. N. A. Bernshteyn's studies on the establishment of movements and the role of different levels of the nervous system in the process are also of great value in understanding the mechanism of forming new coordinations under the unusual conditions of gravitation (ref. 10). /18

Sphere of Regulation of Autonomic Functions

Weightlessness, as mentioned before, may affect the autonomic functions directly as a mechanical factor and indirectly from reflexogenic zones. The main influence, we believe, is manifested by impairment of coordination and in the disruption of the system of self-regulation of autonomic functions. The cardiovascular system is a good example. /19

Loss of the weight of the blood may be responsible for wrong information from the mechanoreceptors of the vascular bed about the state of blood-filling of the corresponding portion of the vascular bed. This, in turn, may cause an inadequate reflex, inadequate redistribution of the blood and unfavorable conditions for cardiac activity. The loss of the "vertical" by the body may result in the pressure gradient in the vascular bed losing one of its functions. It is likely that the appearance of a third cycle in the seismocardiogram of the cosmonauts, described in a paper by one of the authors (Gazenko, ref. 14) was due to such shifts in intracardial hemodynamics.

In most of the cosmonauts, the pulse and respiration rates returned fairly quickly to the original values after the launch part of the flight. Starting on the second and third orbits there was a tendency for the pulse rate to drop below the original level, especially while the cosmonauts were sleeping. For example, Yegorov's pulse rate during the flight was 46 beats per minute. But even on the ground it sometimes dropped to 52 during sleep, testifying to slight predominance of the vagotonic reaction. This is not indicated by the slight prolongation of atrioventricular conduction. /20

On some of the space flights, lowering of the systolic arterial pressure was recorded, as specifically observed by Yegorov in his colleagues. For example, Komarov's systolic arterial pressure dropped from a preflight 115 mm Hg to 95, but the minimum pressure rose from 65 mm Hg to 80. The lowering of the systolic arterial pressure and tendency for the diastolic pressure to rise resulted in slightly lowered pulse pressure in the cosmonauts.

Even more interesting was the tendency for the pulse rate to fluctuate. For example, the reaction of almost all cosmonauts to the transition from sleep to wakefulness was marked by temporary acceleration of the pulse followed by deceleration and longer-lasting changes in the systolic index, time of atrioventricular conduction and shortening of the electric systole.

The cosmonauts of Voskhod and Voskhod-2 noted that even moderate physical exertion produced hidrosis and at times increased tendency to fatigue.

These findings are undoubtedly indicative of changes in the regulation of autonomic functions in weightlessness, some instability of new coordination and regulation of autonomic functions, dystonia and unstable equilibrium between the sympathetic and parasympathetic portions of the autonomic nervous system. One of the authors (Gazenko) presented a physiological interpretation of these phenomena at the Third Symposium on Bioastronautics in Texas in November, 1964. The results will stimulate further research, especially in connection /21 with extended flights.

The cosmonauts of Voskhod-2 exhibited some physiological reactions that had not been observed on any of the preceding flights. After the craft went into orbit, Belyayev's and Leonov's cardiac rate increased slightly. The moderate tachycardia noted was evidently due to the exertions involved in getting the second cosmonaut ready to exit from the ship. At the same time the respiration rate also increased (fig. 1). These reactions are, in general, consistent with those observed in the course of training operations simulating exit.

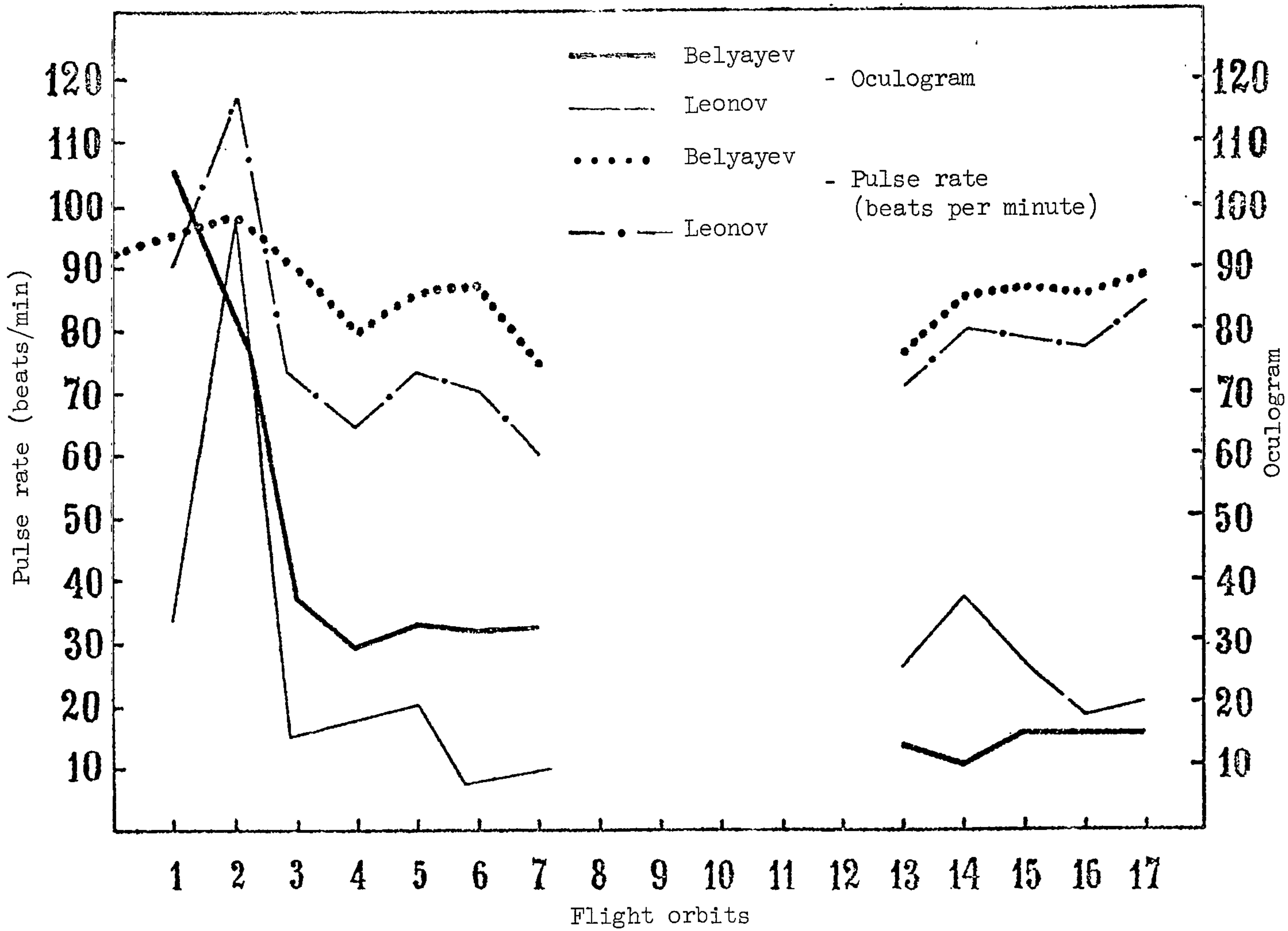
Investigation of Belyayev's and Leonov's oculograms during flight revealed a high rate of eyeball movement between the first and fourth orbits, obviously another indication of the cosmonaut's vigorous activity during this phase of the flight (fig. 1).

Leonov's pulse and respiration rates increased when he was exiting and while outside the vehicle, no doubt due to natural emotional stress. But they quickly returned to normal as soon as he returned to the craft. For example, Leonov's pulse rate was 100-120 beats per min when he finished passing through the airlock, the same values as those recorded during the analogous training exercise on the ground. When he exited, it rose to 150-160, and when he entered the airlock or encountered some difficulties, it rose to 168, but returned to 100-120 fairly quickly as soon as he reentered the airlock (fig. 2).

Analysis of blood samples taken from Feoktistov and Yegorov during the /22 second and twelfth orbits of Voskhod failed to reveal any changes in carbohydrate or salt metabolism. There was a slight increase in blood urea--to 41-51 mg percent (in control samples it never exceeded 40 mg percent). This was obviously an indication of somewhat quicker decomposition of protein during flight. In addition, leukocytosis occurred in Yegorov.

Pulmonary ventilation increased perceptibly during the flight. For example, it increased 2-3 fold in Belyayev and Leonov. Changes in oxygen consumption were ambiguous, and the amount of available data is too limited to permit any definite conclusions.

A comparison of the physiological data recorded during flights of different duration (the Vostoks) with those of the flights of the three cosmonauts (Voskhod) and of the two cosmonauts (Voskhod-2) is useful in evaluating the significance of emotional stress in the picture of the physiological reactions of individual psychophysiological characteristics of the cosmonauts and of the factor of flight duration.


Belyayev
Leonov
- Oculogram
Belyayev
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- Pulse rate
(beats per minute)
Pulse rate (beats/min)
Oculogram
120
110
100
90
80
70
60
50
40
30
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10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Flight orbits

Figure 1

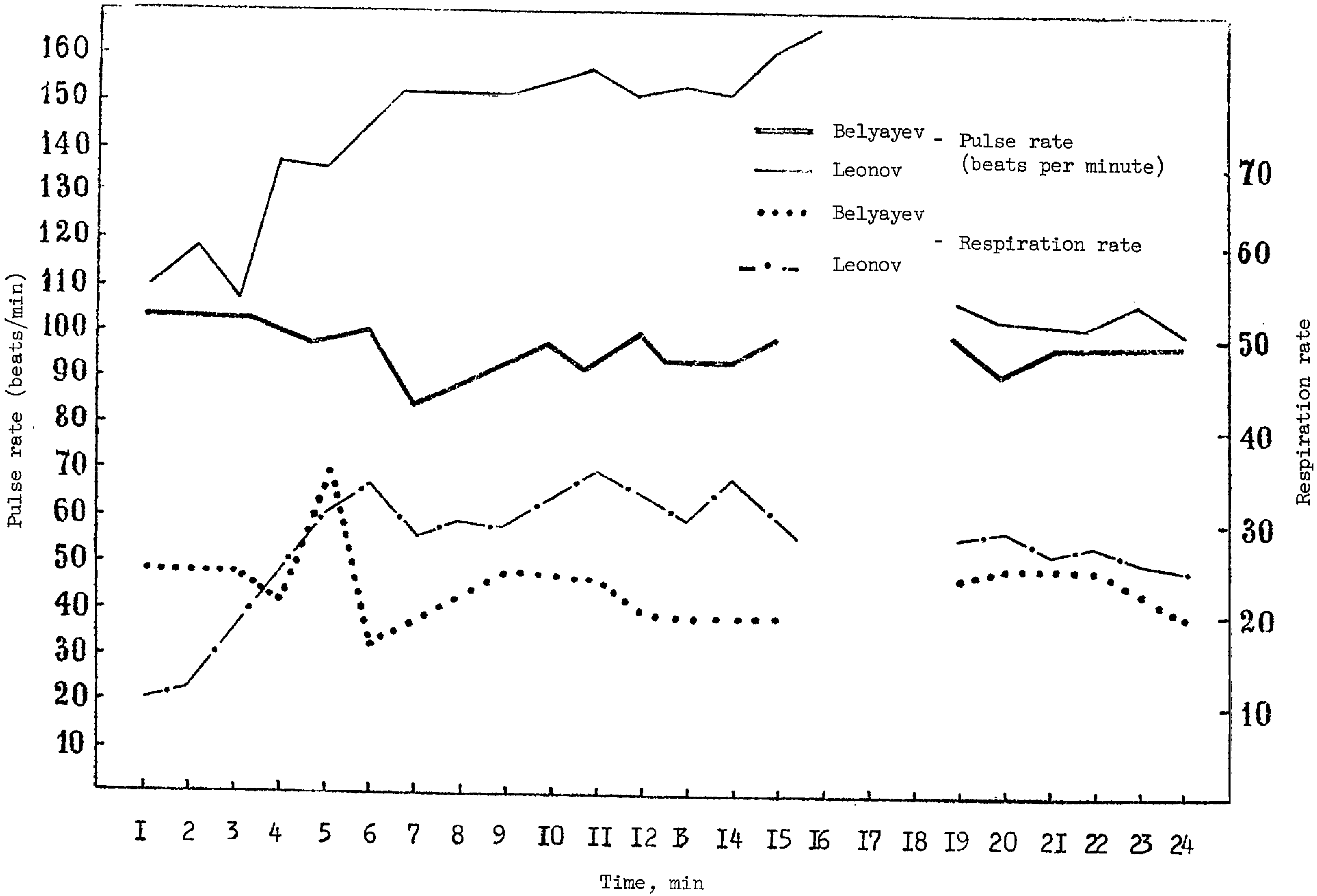
Belyayev
Leonov
- Pulse rate
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Figure 2

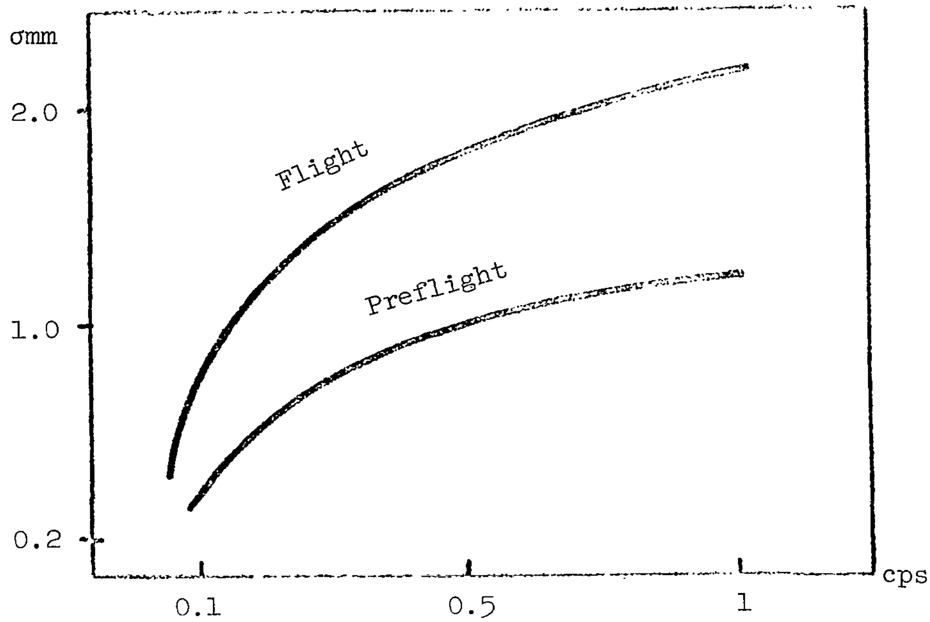

Figure 3. Changes in average error in signal tracking on various frequencies.

It is our impression that the indices of cardiovascular and respiratory function in the crews of Voskhod and Voskhod-2, both before and during the flight, changed less than they did in the cosmonauts who had flown on the Vostoks. For example, the pulse rate of Bykovskiy and Tereshkova was 137 and 151 per min, respectively, whereas it was 98, 102 and 109 per min in Komarov, Feoktistov and Yegorov, respectively (table 1). The transition from acceleration to weightlessness was smooth and, according to the cosmonauts, "imperceptible." /23

Thus, the multimanned flights were definitely superior to the solo flights from the medical and psychological points of view. This is apparent from both the nature and the intensity of the physiological reactions during virtually all stages of the flight, and even in the preflight period. It is easy to perceive the beneficial effect of the "feeling of fellowship."

Twenty-four hours after the flight, functional cardiovascular tests (passive orthostatic test, test with graduated physical exercise) revealed some characteristics of the reactions. For example, the reaction to exercise was somewhat more pronounced, and the restoration period was longer than before the flight. The stroke and minute volumes dropped (in Feoktistov and Yegorov by 26-47 percent) and pulse pressure decreased (by 10-24 mm Hg). Arterial pressure was low in Yegorov after the functional test. /24

Biochemical investigations of blood after the flight showed an increase in cholesterol. For example, the evening after the flight of Voskhod, the

TABLE 1

Space-craft	Cosmonauts	Original values	5 and 1 min before launch and during launch part of the flight, percent of original level		
			5 min	1 min	Launch stage
Vostok-5	V. Bykovskiy	64	207	226	214
Vostok-6	V. Tereshkova	78	162	178	194
Voskhod	V. Komarov	72	152	124	136
Voskhod	K. Feoktistov	76	118	126	134
Voskhod	B. Yegorov	63	136	149	175

cholesterol content of the cosmonauts was 260-290 mg percent instead of their usual 120-180 mg percent. The following morning it dropped to 220-260 mg percent and was completely normal within 2 weeks.

These findings clearly testify to some strain in lipid metabolism due to the flight and to the possibility of prolonged aftereffects.

Postflight investigations of blood sugar in the cosmonauts who flew on Voskhod showed that individual characteristics played a major part. For example, Yegorov normally had a low sugar concentration, whereas it was high in Komarov. Investigations of excretion of 17, 24 oxy-20-ketocorticosteroids, 17-ketosteroids, and the K/Na ratio in urine showed no significant abnormalities. However, these results were obtained after a 24-hour flight, and a more pronounced reaction is to be expected after longer flights.

The day after the flight, Belyayev's energy expenditure exceeded the original values by 29 percent, that of Leonov by only 13 percent.

Forty-eight hours after the flight of Komarov and Yegorov, a functional kidney test showed that water elimination was slower than before the flight or two weeks after it. Neither had any impairment of glomerular filtration or concentration capacity of the kidneys. It is noteworthy that during the flight the cosmonauts did not experience thirst, although the water loss was fairly high. But they felt very thirsty immediately after landing. These changes /25
were probably due to nervous and emotional stress and to hormonal shifts that occurred during flight. Impairment of the water-elimination function may have been related to secretion of an antidiuretic hormone.

The changes in energy expenditure and water metabolism provide additional data to explain the familiar phenomena of weight loss after flight. The cosmonauts of Voskhod and Voskhod-2 lost the following amounts: Komarov, 1.9 kg; Feoktistov, 2.9 kg; Yegorov, 3 kg; Belyayev, 1 kg; Leonov, 0.9 kg.

Thus, the data cited show that the primary physiological effects of weightlessness do not include local changes (e.g., humoral changes), but impairment of neuroreflex regulation and self-regulation. The chain of reactions starts with the change in signals from the receptors, primarily those of the cardiovascular system. Changes in the nature of the signals from the vascular receptors are known to cause radical changes in the regulation of blood circulation (refs. 44 and 48). The latter disrupt the homeostasis needed for the specific activity of various tissues and impair tissue metabolism, which results in trophic disorders.

Postflight medical examinations revealed that the functional changes and unstable regulation of autonomic functions (as shown, e.g., in exercise tests) persisted for some time after the flight. /26

It is well to note here the danger inherent in the cosmonauts' reactions to the shift from acceleration to weightlessness and from weightlessness to acceleration (refs. 14, 18, 19, 31 and 39). During the transition from weightlessness to acceleration, resistance to the overload by the organism in a state of unstable reconstitution of autonomic functions will probably be weak. Indeed, the cosmonauts have often stated that it is harder to tolerate acceleration when the spacecraft returns to Earth than when it goes into orbit (refs. 14, 26 and 39).

During the active part of the flight, the pulse and respiration rates were much more rapid than when the men were exposed to equivalent acceleration on a centrifuge. And it took much longer for these indices to return to the original values when the acceleration in space flight ceased (refs. 8, 14, 39 and 47). This period was particularly long on the flight of Voskhod-2, which we attributed to the activity of the cosmonauts in preparing for the "exit" from the craft.

It follows from the foregoing that the cosmonauts' reactions depend on a host of factors. We must take into account both the qualitative and quantitative characteristics of the effects of several factors operating simultaneously, the order in which they occur, the various external and internal conditions, one of the most important of which is the general condition of the organism, /27 especially the nervous system, and the preceding preparation and training. It is clear, therefore, that it is not sufficient to study only the effects of the individual flight factors; the influence of the entire set must be evaluated (refs. 13 and 21). This is an urgent problem requiring special consideration, but it is outside the scope of the present communication.

Thus, here also we see the value of using the synthetic principle in studying the physiological effects of gravitation (refs. 21, 23, 35 and 38).

Conclusions /28

Some of our preliminary conclusions from the material presented here are as follows.

The direct influence of weightlessness as a mechanical factor on the course of physiological processes is probably not of great significance. The primary effects are changes in the receptor functions and in the afferent sphere. The flow of afferent impulses, unusual in total number and quality, are responsible for these main reactions:

(1) general nonspecific stress reaction;

(2) impairment of perception by external and internal analyzers, (intero- and proprioceptive signal systems), which gives rise to illusions (including impairment of spatial orientation, spatial analysis);

(3) inadequate reactions by the viscera, disruption of self-regulation and coordination of autonomic functions, the vestibular-autonomic disturbances;

(4) impairment of coordination of movements and decrease in operational efficiency.

Immediately after the shift to weightlessness and thereafter, the following mechanisms of adaptation to the unusual gravitational conditions, the mechanisms of compensation and vicarious activity of impaired and lost functions, are activated:

(1) mechanisms of nonspecific adaptation, which border closely on the stress reaction;

(2) reconstitution in the afferent sphere; new coordination of analyzer activity resulting in a maximally complete and accurate reflection of the world under the unusual gravitational conditions (this reconstitution is achieved under the control of and with corrections introduced by the higher divisions of the central nervous system, the cerebral cortex in particular); /29

(3) reconstitution in regulation of activity of the viscera; new coordination of their activity aimed at ensuring homeostasis and providing scope for the functional capabilities of the organism (with phases of more or less complete compensation of impaired functions; but even with satisfactory compensation, the organism's reserves are somewhat limited, as revealed when loads are applied); the new coordination shows signs of being somewhat inadequate (at least during short flights);

(4) reconstitution in the sphere of somatic functions; the new coordination of movements is achieved under the control and with the extensive participation of the higher divisions of the central nervous system; preliminary preparation and training play an important part by ensuring compensation (adaptation and vicarization) of both elementary skills and complex types of activity. There are indications, however, that compensation is not always complete (at least during short flights).

Recommendations

The long-range plans that call for more distant and extended flights, in which the cosmonauts will have complex steering and research duties, require /30 suitable practical measures for selecting and training personnel and creating optimum working conditions and routines, as well as preventive and protective devices.

A thorough and systematic study of the effects of flight factors (weightlessness in particular) and the mechanisms of adaptation to them will be of value in predicting reactions on various space routes and in working up a sound program for the flights, cosmonauts' activities and protective measures.

In selecting personnel, it is obviously essential to take into account the individual characteristics of plasticity and lability of the central nervous system, and its capacity to reorganize old coordinations in the afferent and efferent spheres and in the activity of the viscera in accordance with new environmental conditions. This capacity must be strengthened during the training period.

It is necessary to study the role of the individual parts of the central nervous system (e.g., the cerebellum and sympathetic nervous system) in reconstructing coordinations to suit environmental conditions, and to investigate the possibility of using pharmacological or other agents to assist in the various stages of the process.

Use should be made of the possibility of nonspecific training and of increasing man's adaptive capabilities, e.g., by staying in high-altitude regions (refs. 5 and 11).

Efficient methods of preparation and training should be devised to facilitate the reorganization of the body, so that it can adequately cope with flight conditions. A good example of this was Leonov's training for orientation /31 in space with the aid of artificial coordinates orienting points. Some other working dominants might be devised to prevent vestibular-autonomic disturbances.

We believe that only the first few steps have been taken in this direction. Ahead of us lies much arduous, but extremely interesting and, we hope, fruitful work. This work which promises to solve practical problems in astronautics also has major implications for important theoretical problems in biology and medicine. The goal is worthy of the friendly and cooperative efforts of scientists all over the world.

REFERENCES

1. Ayrapet'yants, E. Sh. and Lichkus, K. V. Trudy instituta fiziologii im. I. P. Pavlova, Vol. 6, Moscow-Leningrad, Izd-vo AN SSSR, 1958.

2. Ayrapet'yants, E. Sh. and Kislyakov, V. A. Uspekhi Sovremennoy Biologii, Vol. 63, No. 3, 1957.

3. Ayrapet'yants, E. Sh., Batuyev, A. S., Kislyakov, V. A. and Lebentrau, K. Fiziologicheskiy Zhurnal SSSR, Vol. 64, No. 8, 1960.

4. Ayrapet'yants, E. Sh. In: Aspects of the Comparative Physiology of Analyzers (Voprosy Sravnitel'noy fiziologii analizatorov), Vol. 1, Leningrad, Izd-vo LGU, 1960.

5. Barbashova, Z. I. Acclimatization to Hypoxia and Its Physiological Mechanisms (Akklimatizatsiya k gipoksii i yeye fiziologicheskiye mekhanizmy). Moscow-Leningrad, Izd-vo AN SSSR, 1960.

6. Batuyev, A. S. Nauchnyye doklady vysshey shkoly. Biologicheskiye Nauki, No. 2, 1960.

7. Batuyev, A. S. and Dymnikova, O. P. In: Aspects of the Comparative Physiology of Analyzers (Voprosy Sravnitel'noy fiziologii analizatorov), Vol. 1, Leningrad, Izd-vo LGU, 1960.

8. Beckh, H. V. Astronautics, Vol. 4, No. 2, 1959.

9. Beritashvili, I. S. Nerve Mechanisms of Spatial Orientation in the Higher Vertebrates (O nervnykh mekhanizmakh prostranstvennoy oriyentatsii vysshikh pozvonochnykh zhivotnykh). Tiflis, Izd-vo AN GruzSSR, 1959.

10. Bernshteyn, N. A. Construction of Movements (O postroyenii dvizheniy). Moscow, Medgiz, 1947.

11. Bioastronautics, Randolph School of Aviation Medicine, 1956.

12. Vatsuro, E. G Investigation of Higher Nervous Activity in the Anthropoid Apes (Chimpanzees) (Izzledovaniye vysshey nervnoy deyatel'nosti antropoida (shimpanze)). Moscow, Izd-vo AMN SSSR, 1948.

13. Effect of Ionizing Radiation and Dynamic Factors on Central Nervous System Function (Vliyaniye ioniziruyushchikh izlucheniy i dinamicheskikh faktorov na funktsii tsentral'noy nervnoy sistemy). Moscow, Izd-vo "Nauka," 1964.

14. Gazenko, O. G. Third International Symposium on Bioastronautics. San Antonio, November 1964.

15. Gazenko, O. G. and Gyurdzhian, A. A. On the Biological Role of Gravity. COSPAR Symposium, Florence, Italy, May 1964.

16. Gauer, O. H. and Zuidema, G. D. Gravitational Stress in Aerospace Medicine. Little, Brown and Co., Boston, 1961.

17. Gerathewohl, S. J. J. of Aviation Medicine, Vol. 25, No. 4, 1954.

18. Graveline, D. E. Aerospace Medicine, Vol. 33, p. 297, 1962.

19. Graveline, D. E. and McCally, M. Aerospace Medicine, Vol. 33, p. 1281, 1962.

20. Gualtierotti, Margaria R. 14th International Astronaut. Cong., Paris, 1963.

21. Gyurdzhian, A. A. 22nd Int. Cong. Physiol. Sci., Vol. 1, Part 2, pp. 909-914, 1962.

22. Gyurdzhian, A. A. et al. Effect of Ionizing Radiation and Dynamic Factors on Central Nervous System Function (Vliyaniye ioniziruyushchikh izlucheniy i dinamicheskikh faktorov na funktsii tsentral'noy sistemy). Moscow, Izd-vo "Nauka," 1964.

23. Yemel'yanov, M. D., Kuznetsov, A. G., Yuganov, Ye. M. and Gyurdzhian, A. A. In: Man in Space. Vienna, Springer-Verlag, 1965.

24. Zimkin, N. V. Fiziologicheskiy Zhurnal, Vol. 50, No. 6, 1964.

25. Isakov, P. K. In: Aviation and Space Medicine (Aviatsionnaya i kosmicheskaya meditsina), Moscow, 1963.

26. Johnson, R S., Hays, E. L. and Dietlin, L. F. 14th International Astronaut. Cong., Paris, 1963.

27. Loret, B. J. Aerospace Med., Vol. 34, No. 5, 1963.

28. Kas'yan, I. I. and Kopanev, V. I. Izvestiya AN SSSR, Seriya Biologicheskaya, No. 6, 1963.

29. Kas'yan, I. I., Kopanev, V. I. and Yuganov, Ye. M. Acclimatization to Hypoxia and Its Physiological Mechanisms (Akklimatizatsiya k gipoksii i yeye fiziologicheskiye mekhanizmy). Moscow-Leningrad, Izd-vo AN SSSR, No. 5, 1964.

30. Komendantov, G. L. Physiological Foundations of Spatial Orientation (Fiziologicheskiye osnovy prostranstvennoy orientirovki). Leningrad, 1959.

31. Kotovskaya, A. R., Kakurin, L. I., Simpura, S. F. and Grishina, I. S. Problems of Space Biology (Problemy kosmicheskoy biologii), Vol. 4, Moscow, Izd-vo "Nauka," 1965.

32. Lansberg, M. P. A Primer of Space Medicine. Amsterdam, 1960.

33. Mantsvetova, A. I., Neumyvakin, I. P., Orlova, V. F., Trubnikova, V. A. and Freydberg, I. M. Kosmicheskiye Issledovaniya, No. 4, 1964.

34. Mogendovich, M. R. Reflex Interaction of the Locomotor and Visceral Systems (Reflektornoye vzaimodeystviye lokomotornoy i vistseral'noy sistem), Medgiz, 1957.

35. Orbeli, L. A. Problems in Higher Nervous Activity (Voprosy vysshey nervnoy deyatel'nosti). Moscow-Leningrad, Izd-vo AN SSSR, 1949.

36. First Manned Space Flights (Pervyye kosmicheskiye polety cheloveka). Moscow, Izd-vo AN SSSR, 1962.

37. First Multimanned Space Flight (Pervyy gruppovoy kosmicheskiy polet), Moscow, Izd-vo "Nauka," 1964.

38. Pavlov, I. P. Collected Writings, 6 volumes, Izd-vo AN SSSR, 1951.

39. Parin, V. V., Volynkin, Yu. M. and Vassilyev, P. V. COSPAR Symposium, Florence, Italy, May 1964.

40. Pestov, I. D. Izvestiya AN SSSR, seriya biologicheskaya, No. 5, 1964.

41. Preliminary Results of Scientific Investigations by Means of the First Soviet Earth Satellites and Rockets (Predvaritel'nyye itogi nauchnykh issledovaniy s pomosch'yu pervykh sovetskikh iskusstvennykh sputnikov Zemli i raket). Moscow, Izd-vo AN SSSR, 1959.

42. Problems in Space Biology (Problemy kosmicheskoy biologii), Vol. 1, Moscow, Izd-vo AN SSSR, 1962.

43. Sechenov, I. M. Physiology of the Nervous System. Selected Writings (Fiziologiya nervnoy sistemy. Izbrannyye trudy), 4 volumes, Moscow, Medgiz, 1952.

44. Khayutin, V. M. Vasomotor Reflexes (Sosudodvigatel'nyye refleksy). Moscow, Izd-vo "Nauka," 1964.

45. Khilov, K. L. Cerebral Cortex in Vestibular Function (Kora golovnogo mozga v funktsii vestibulyarnogo analizatora), Moscow-Leningrad, 1952.

46. --- Selected Aspects of the Theory and Practice of Space Medicine from the Standpoint of Labyrinthology (Izbrannyye voprosy teorii i praktiki kosmicheskoy meditsiny s pozitsiy labirintologii). Leningrad, 1964.

47. Chernov, V. N. and Yakovlev, V. I. In the collection: Iskusstvennyye Sputniki Zemli. Vol. 1, Izd-vo AN SSSR, 1958.

48. Chernigovskiy, V. N. Interoceptors (Interotseptory). Medgiz, 1960.

49. Chkhaidze, L. V. Coordination of Human Voluntary Movements during Space Flight (Koordinatsiya proizvol'nykh dvizheniy cheloveka v usloviyakh kosmicheskogo poleta). Moscow, Izd-vo "Nauka," 1965.

50. Ukhtomskiy, A. A. Collected Writings, Vol. 4, Leningrad, Izd-vo LGU, 1945.

51. Vrabiescu, A., Cimpeanu, Z. and Domilescu, C. Third International Symposium on Bioastronautics. San Antonio, November 1964.

52. Wunder, C. C. and Lutherer, L. O. Influence of Chronic Exposure to Increased Gravity upon Growth and Form of Animals. Internat. Rev. of Gen. and Experimental Zoology, Vol. 1, Acad. Press, New York, 1964.

53. Yuganov, Ye. M. Voyenno-Meditsinskiy Zhurnal, No. 7, 1955.

54. Yuganov, Ye. M. and Gorshkov, A. I. In: Problems of Space Biology (Problemy kosmicheskoy biologii), Vol. 3, Moscow, Izd-vo "Nauka," 1964.

55. Yuganov, Ye. M. and Zakhmatov, D. M. Voyenno-Meditsinskiy Zhurnal, No. 4, 1958.

56. Yuganov, Ye. M., Kas'yan, I. I., Cherepakhin, M. A. and Gorshkov, A. I. Problems of Space Biology (Problemy kosmicheskoy biologii), Vol. 2, Izd-vo AN SSSR, 1962.

57. Yuganov, Ye. M., Kas'yan, I. I., Gurovskiy, N. N. et al. Izvestiya AN SSSR, Seriya Biologicheskaya, No. 6, 1961.

58. Yuganov, Ye. M., Sidel'nikov, I. A., Gorshkov, A. I. and Kas'yan, I. I. Izvestiya AN SSSR, Seriya Biologicheskaya, No. 3, 1964.

59. Yuganov, Ye. M., Kas'yan, I. I. and Yazdovskiy, V. I. Izvestiya AN SSSR, Seriya Biologicheskaya, No. 4, 1964.

60. Yazdovskiy, V. I. and Yemel'yanov, M. D. Problems of Space Biology (Problemy kosmicheskoy biologii), Vol. 3, Izd-vo "Nauka," 1964.

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